The Effects of Implied Motion Training on General Cortical Processing

by

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ABSTRACT

Current research has identified a specific type of visual experience that leads to faster cortical processing. Specifically, performance on perceptual learning of a directional-motion leads to faster cortical processing. This is important on two levels; first, cortical processing is positively correlated with cognitive functions and inversely related to age, frontal lobe lesions, and some cognitive disorders. Second, temporal processing has been shown to be relatively stable over time. In order to expand on this line of research, we examined the effects of a different, but relevant visual experience (i.e., implied motion) on cortical processing. Previous fMRI studies have indicated that static images that imply motion activate area V5 or middle temporal/medial superior temporal complex (MT/MST+) of the visual cortex, the same brain region that is activated in response to real motion. Therefore, we hypothesized that visual experience of implied motion may parallel the positive relationship between real directional-motion and cortical processing. Seven subjects participated in a visual task of implied motion for 4 days, and a pre- and post-test of cortical processing. The results indicated that performance on implied motion is systematically different from performance on a dot motion task. Despite individual differences in performance, overall cortical processing increased from day 1 to day 4.

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Perceptual learning is broadly defined as improvement in sensory perception by way of training over time (Fahle, 2005). In addition, perceptual learning has been found to be highly specific to low-level features (i.e., contrast, direction, orientation, location, etc). For example, learning to discriminate motion in one location will not transfer to a location equal to and greater than 3 degrees away, which is within the primary visual cortex[1]. That is, neurons firing rate drops to baseline when location, direction, orientation of the stimuli is shifted (Fahle, 2005). Moreover, the high specificity suggests that cells in V1 integrate multiple low-levels features for more complex visual processing. For example, moving dots at 10 percent coherency (local motion) within randomly distributed dots will appear to move in one direction (global motion). Taken together, the integration suggests that V1 extracts great amount of information from single low-level features. The high specificity of perceptual learning has been empirically linked to a biological process of neuroplasticity, which is a functional (performance enhancement) and structural (increase in synaptic pathways) enhancement to novel changes in the environment. This neuro-biological process explains how we learn and adapt quickly and proficiently to new information in our environment (Fahle & Poggio, 2002).

Researchers have been exploring the generalizability of perceptual learning within low-level (e.g., change in location) and high-level visual processing (e.g., complex visual processing). For example, Crist, Kapadia, Westheimer, & Gilbert, (1997) found that performance in three-line bisection task[2] transferred up to eight degrees from the training field, which is beyond the primary visual cortex. Furthermore, perceptual learning of coherent dot motion, where subjects discriminate direction of a specified group of dots

within a randomly moving dot field, led to a significant increase in flicker perception (high-level visual process). Very recent studies have indicated that perceptual learning of motion does not only lead to faster flicker perception, but also faster reading speed and better reading comprehension (Holloway, Nanez, & Seitz, under revision; Groth, (2013, unpublished MS thesis).

The dual system theory has been proposed to explain the systems of low- and high- level visual processing, and the interaction between the two levels (Milner & Goodale, 2007). According to the Milner and Goodale (2007), humans have two distinct, but mutually independent visual systems, which consist of visual streams for action (i.e., the dorsal stream) and perception (i.e., ventral stream). More specifically, when exposed to visual stimuli (i.e., moving dots), the information is carried from the ganglion cells within the retina to the magnocellualr pathways (large layer of cells within the lateral geniculate nucleus), then to the primary visual cortex for processing (V1). From V1, depending on the visual stimuli, the information travels through either the dorsal stream ("where pathway") or the ventral stream ("what pathway"). If the stimulus is fast moving low-contrast dots, the information travels from V1 to the MT and parietal lobe for higher-order processing (e.g., where tasks like flicker perception, word decoding, reading comprehension are processed) via the dorsal stream. If subjects are instructed to identify an object that is presented at a slower rate with higher contrast, then the information is projected to the inferior temporal cortex through the ventral stream (Nealey & Maunsell, 1994).

In regards to our motion discrimination task, specifically, the neural properties of area MT provide the theoretical framework for the current study. Moreover, area MT has

been shown to be directionally tuned (Priebe & Lisberger, 2002), which referees to decrease in neural activity when an observer is repeatedly exposed to the same direction of motion. In addition, area MT has demonstrated an increase in functional benefit when exposed to novel motion (Kohn, 2007; Ranganath & Rainer, 2003). Essentially, motion discrimination training that is randomly displayed throughout the experiment is structurally and functionally beneficial for area MT. In this paper, we are only interested in the neural correlates of V5 or medial temporal through the dorsal stream. The neural correlates of magnocallular pathway, MT/MST+, and the dorsal stream may provide the theoretical framework for the variables of interest in this paper. That is to say, the variables of interest include fast moving, low contrast, unidirectional-implied motion. Each component of the variable is related to low-level and high-level visual processing.

Implied motion is broadly defined as static stimuli that imply motion due to dynamic features within the stimuli (Kourtzi & Kanwisher, 2000). For example, the image of a silhouette in Figure 1 is implying motion to the left with high leg-left, arched back, and extended arms. In contrast, the image of a woman in Figure 3 is motionless because she lacks the articulation in body posture needed to imply motion. Previous research has indicated that images resembling Figure 1 activate area MT/MST+ significantly higher than the images resembling Figure 3. Kourtzi and Kanwisher, (2000) argued that MT/MST+ is not the only brain region responsible for processing visual cues that imply motion; rather it is part of a larger network of brain regions that "mediate" the visual processing of motion. In addition, they reasoned that MT/MST+ sensitivity of implied motion are, in part, governed by a top-down influence. In other words, the adult brain has been exposed to similar animate objects (i.e., biological figure of a silhouette),

which influence the processing of the visual stimuli (i.e., motion). Functional Magnetic Resonance Imaging (fMRI) studies of implied motion following Kourtzi & Kanwisher, (2000) have confirmed the top-down influence, by showing neural correlates beyond MT/MST+. For example, researchers have found activation in superior temporal sulcus (STS; sensitive to dynamic biological forms), extrastriate body area (EBA; sensitive to body type), and pre-motor and motor cortex (sensitive to high degree of articulation) (Proverbio, Riva, & Zani, 2009; Jellema & Perrett, 2003). In addition, Fawcett, Hillebrand, & Singh, (2007) and Lorteije et al., (2006) found late activation (600 ms-900ms) in MT, suggesting the influence of higher-level processing. However, researchers also argue that activation of implied motion could be due to differences in low-level features (Lorteije et al., 2011; Pavan, Cuturi, Maniglia, Casco, & Campana, 2011).

The discrepancy regarding neural correlates of implied motion could be due to differences in experimental methodology (e.g., controlling for low level features, contrast, and timing). It is evident that there are no standardized methods of presenting implied motion in regards to timing and image properties (e.g., color, size, contrast, etc). For example, the stimuli include, but are not limited to, grayscale images of (in)animate objects (Kourtzi, & Kanwisher, (2000); Jellema & Perrett 2003; Pavan, Cuturi, Maniglia, Casco, & Campana (2011), color images of (in)animate (Winawer, Huk, & Boroditsky, (2008), Fawcett, Hillebrand, & Singh, (2007); Holmes & Wolff, (2010), color images of hand in grasping movement (Urgesi, Moro, Candidi, & Aglioti, (2006), and cartoon images in articulated positions (Osaka, Matsuyoshi, Ikeda, & Osaka, (2010). In addition, the presentation of the stimuli varies as a function of experimenters' parameter (i.e., motion perception, motor perception, and time perception) from approximately 25ms to

2000ms, and up to 60000ms (Kourtzi & Kanwisher, (2000); Lorteije et al., 2006; Winawer, Huk, & Boroditsky, (2008), Fawcett, Hillebrand, & Singh, (2007), Urgesi, Moro, Candidi, & Aglioti, (2006). Taken together, the image properties and the rate of presentation may influence different regions of the brain in a top-down process. For example, in a study by Proverbio, Riva, & Zani, (2009), participants were exposed to relatively bright (i.e., 47.88 cd/m^2) and detailed colorful images of humans (e.g., athletic women running) presented at a rate of 1500 millisecond (ms) per frame. They found activation in MT, EBA, STS, pre-motor (BA-6), motor areas (BA-4), cingulate, and IF cortex. The method and features of the stimuli may, in part, explain the area of the brain that was activated in conjunction with area MT/MT+. In this paper, the properties of the stimuli and the rate of presentation were strategically chosen to reduce the influence of high-order processing on area MT/MST+.

Interestingly, implied motion is not limited to physical stimuli, but also non-physical and imaginary stimuli (Saygin, McCullough, Alac, & Emmorey, (2010), Tartaglia, Bamert, Mast, & Herzog (2009); Tartaglia, Bamert, Herzog, & Mast, 2012). For example, Saygin, McCullough, Alac, & Emmorey, (2010) found that motion sentences (i.e., sentences that include verbs) activated area MT+ at significantly higher rate than static sentences (e.g., sentence that does not describe action). Furthermore, there are two studies (Tartaglia, Bamert, Mast, & Herzog (2009); Tartaglia, Bamert, Herzog, & Mast, 2012) that examined the effects of perceptual training of imaginary stimuli on performance of real stimuli. More specifically, Tartaglia, Bamert, Mast, & Herzog (2009) showed that by instructing participants to imagine the offset of the middle line in a three-line bisection task[2], improved performance on a bisection task with three physical lines.

Note that participants received auditory cues for offset to the left (low frequency tone) and offset to the right (high frequency tone). Tartaglia, Bamert, Herzog, & Mast, (2012) successfully expanded on the three-line bisection task study through the examination of an imaginary motion discrimination task. Performance on imaginary motion discrimination task led to performance enhancement in real motion discrimination task. It has been empirically shown that multisensory feedback (audio or visual) increase performance in visual perception tasks (Seitz, Kim, & Shams, 2006). Based on pervious literature, multisensory feedback was utilized to enhance performance in implied motion training.

Although there is growing interest in neural correlates of implied motion, no study, to our knowledge, has examined the effects of implied motion, as a visual experience, on low- and high-level cortical processing. The goal of this paper is to expand on Seitz, Nanez, Holloway, & Watanabe's, (2006) findings, through examination of implied motion training. They found that perceptual learning of directional-motion (i.e., visual experience) led to higher Critical Flicker Fusion Threshold (CFFT) (i.e., alteration of cortical processing). More specifically, functional change in motion-direction accompanied significant change in temporal processing of flicker perception, compared to control, non-coherent motion, and no-motion groups. Therefore, directional motion is an important visual cue that will be utilized in this study.

CFFT refers to a critical frequency of intermittent light (i.e., number of on and off flicker per second) that are perceived as steady continuous light to the human observer. Previous research has indicated that CFFT is inversely correlated with frontal lobe lesions (Halstead, 1947); mental disorders (Saucer & Sweetbaum, 1958; Curran & Wattis, (2000)

autoimmune disease (Sandry, 1963), fatigue (Hosokawa, Mikami, & Saito, 1997), and age (Hindmarch, 1988). Importantly, CFFT is positively correlated with visual experience of directional-motion (Seitz, Watanabe 2003; Seitz et al 2006), intelligence (Halstead 1947), reading speed and comprehension (Groth 2013), and word decoding (Nanez, Holloway, Donahoe, & Seitz, 2006). Moreover, single-cell (Colby, Duhamel, Goldberg, 1993), Seitz and Watanabe (2005); Seitz, Nanez, Holloway, & Watanabe, (2006) and lesion studies (Merigan, Byrne, Maunsell, 1991; Schiller, Logothetis, & Charles, 1991) have indicated that the megnocellaur pathway is particularly sensitive to flicker perception. The magnocelluar pathway, as discussed above, activates to fast moving and low contrast stimuli. In this paper, CFFT was operationalized as general cortical processing or how fast the observer processes information.

The purpose of this experiment was to examine the effects of a performance-dependent task consisting of unidirectional-implied-motion on CFFT. First, we evaluated the validity of the implied motion. Second, we examined the validity of the implied motion training. Third, we examined whether performance on implied motion training parallels performance on a real motion task. In the dot motion task paradigm, performance increases as a function of time and practice. Fourth, we examined luminance difficulty and training days on performance. Fifth, we examined the relationship between exposure to implied motion training and CFFT. Based on previous literature, we hypothesis that performance in detecting the direction of implied motion would increase over the four days of training. Second, we hypothesized that enhancement in implied motion training should lead to faster CFFT.

Methods

Participants

Seven students (Males = 3, Females = 4, age = 18-48 years, *M* = 26.38, SD = 9.03) were recruited from Arizona State University West Campus. Students were compensated for their time and effort. All participants reported good visual health on a subjective survey and met the 20/40 visual acuity cut off line. Participants signed a consent form and were told that they could quit the experiment at any time. Finally, participants were naïve to the goals of the experiment.

Materials and procedure

Stimuli were presented on 24'' 2407WFP-HC monitor at a resolution of 1920 x 1200 at 76 Hz refresh rate. The experiment was conducted using custom software.

The implied motion stimulus follows the image properties of previous literature (Kourtzi, Kanwisher, 2000; Lorteije et al., 2011). The most frequent visual cues used to imply motion include high articulation in body posture and motion blur. In this study, three software programs were used to control for orientation, luminance, size of stimulus, and visual cues. For example, the shape and the articulation of silhouettes were designed on DAZ Studio 4.6 software. The articulations of the silhouettes varied (categorically) from low speed (little or no implied motion; Figure 3), medium (low implied motion; Figure 2) and to high (high implied motion; Figure 1). Photoshop Software was used to modify stimulus size (32.4° x 18.56°), contrast levels (luminance Y ≈ .6, .9, 1.2, 1.9), motion blur (5 pixels at 34°), and orientation (54°, 124°, 270°, 320°).

Implied Motion task

The implied motion task was designed to expose participants to different luminance levels, to expose participants with systematic presentation of directional implied motion, and to reduce the effects of habituation. Taken together, it has been shown that all three components (i.e., contrast levels, unidirectional, and reduction of habitation) are needed for effective functional change in visual processing (Kohn, 2007; Ranganath & Rainer, 2003).

First, participants were presented with white fixation point for 300 ms, followed by a silhouette figure on one of four off-cardinal directions (54°, 124°, 270°, 320°) at different contrast levels (relative luminance Y ≈ .6, .9, 1.2, 1.9) for 250 ms. After a silhouette image was presented, a response screen appeared to collect the participants answers. The response screen had four arrows corresponding to the direction of the silhouette. Once the participants responded, an audio and visual feedback was provided. The feedback included a high-pitched tone coupled with a green "O" symbol for correct response and low-pitch tone coupled with "X" symbol for incorrect response (see Figure 10). The direction of the silhouettes and the contrast levels were randomized across each frame (i.e., trails) and subjects. Finally, the task was designed to increase or decrease in difficulty based on participants' performance. All participants completed a total of 800 trails per day x four total days of training equaling to 3200 total frames. Software diagnostics were conducted to examine if the correct stimulus were presented, and if the performance-based equation was working properly.

CFFT was measured using a Macular Pigment Optical Densitometer (Wooten, Hammond Jr, Land, & Snodderly, 1999). CFFT was calculated psychophysically by measuring each participant's sensitivity to a green light (peak wavelength = 550 nm at

1.5 cd/m^2) flickered on a solid blue background (peak wavelength = 460 nm at 4.3 cd/m^2) in a 1° circle. The experimenter increases the frequency (Hz) of green light (i.e., at equal counter-phase) until the stimulus appears to be a steady light. After this point was established and recorded, the rate of frequency is then increased by 10 Hz, and decreased until the light appears to be flickering again. CFFT was calculated as the average between the frequency at which the light appears to be a steady and the frequency at which the light appears to be flickering. This is measured six times in order to attain an unbiased average for each participant.

The experiment will follow the protocol of Seitz, Nanez, Holloway, & Watanabe, (2006) study. That is, Participants' head movements were constrained with a chinrest. The viewing distance of participants was 3 feet away from the monitor. The room was dimly lit at 1.5 cd/m^2. Finally, the experiment included a 4 days of implied motion discrimination training, and pre-and post testing of CFFT on day 1 and day 4.

Results

First, we evaluated the efficacy of the implied motion stimulus used in this study. Previous research has indicated a top-down influence of neural activity on processing of implied motion. That is, there is lag in neural activity when subjects are exposed to an implied motion stimulus. We examined the accuracy of the visual cues using reaction time as the outcome variable. More specifically, we examined the difference in reaction time when participants were exposed to motion blur vs. no motion blur, and when participants were exposed to low, medium, and high degree of articulation. Motion blur refers to streaks surrounding the silhouettes body to imply motion and speed. The results indicated that reaction time to blurred images (M = 840.66 ms) was significantly higher

than to images without blur (M = 797.43 ms, F (1, 24626) = 9.08 p < .01) (Table 3). In addition, there was a main effect of degree of articulation on latency, F(2, 24626) = 4.54 p < .05) (Table 3). Post hoc analysis using Tukey's Honestly Significant Difference correction indicated that reaction time for low articulation (M = 796.92 ms) was significantly lower than high articulation (M = 846.66 ms, p < .02) (Table 4). No other significant differences were found. As expected reaction time by articulation (Figure 5) and motion (Figure 6) decreased each day, and equalized by day 4. In summary, the visual cues of the stimulus in this study are consistent with the psychophysical and imagining studies of implied motion (Urgesi, Moro, Candidi, & Aglioti, 2006).

Second, we evaluated the validity of the implied motion task software program. More specifically, we examined the performance-based equation (increase or decrease in difficulty based on observer performance), and proper display of the stimulus. Frequency analyses and a One-way ANOVA were conducted to examine the frequency of stimulus exposure and performance on different levels of luminance, respectively. The One-way ANOVA indicated that there was a significant difference between luminance levels and performance, F (3, 12744) = 914.190, p< .001) (Table 5). Furthermore, post-hoc tests using Bonferroni indicated that participants performed at chance level for luminance 0.6Y (M = .50), below chance level for luminance .9 Y (M = .25, p< .05), and above chance for high luminance 1.20 Y and 1.90 (M = .57, M =.84, respectively) (Table 6). Interestingly, participants performed better on sub-luminal-equivalent luminance level (Y≈ .6 [below visual awareness)] than they did on the supraliminal-equivalent luminance level (Y≈ .9 [at visual awareness]) (M = .25, p< .05) (Table 10). This finding may be due to the stimulus properties. That is, participants were able to observe the stimulus at

luminance of .9Y but were unable to indicate the direction the silhouette was facing, which increased the probability of choosing the incorrect direction. Possibilities for this finding are presented in the Discussion section below.

Third, we examined whether the performance pattern on the implied motion task parallel the linear trend found in perceptual learning of real motion task. As discussed above, gradual, linear increase over the 4 days of training would suggest the presence of perceptual learning of implied motion. A repeated measure ANOVA was conducted to examine the change in performance over the 4 days training phase of the experiment. The Greenhouse-Geisser correction indicated a significant difference in performance over the four days, F (2.99, 13752.39) = 21.47, $p < .001$, $\eta_p^2 = .01$ (Table 7). Furthermore, polynomial contrast analyses indicated that the difference in performance could be explained by a quadratic function, $F(1, 4586) = 41.36$, $p < .001$, $\eta_p^2 = .01$ (Table 8). That is, when compared to day 1 (baseline) ($M = .53$) performance significantly increased in day 2 ($M = .56$), did not change in day 3 ($M = .54$), and significantly decreased below threshold in day 4 ($M = .48$) (Figure 6). These results suggest that the point of saturation (overtraining) occurred after day 2 (Censor & Sagi 2008). According to Censor and Sagi (2008), overtraining or over-exposure to a specific type of stimulus will result in saturation, which should reduce how participants effectively process information.

Fourth, we examined luminance levels and training day as predictors of performance. This analysis was conducted to reduce the chance of committing a Type I error (William, Shadish, Cook, & Campbell, 2002). Two-way analyses of variance were conducted to examine the main effects of luminance, days of training, and the interaction effect between days of training and luminance. The analysis indicated that there is

significant main effect of luminance on performance, $F(3, 12719) = 884.00$, $p < .001$, $\eta_p^2 = .17$) (Table 10). However, there are no significant difference between performance and number of training days (p = ns). The result suggests that partitioning the influence of luminance on performance reduces the significant level of day. In addition, the results indicated an interaction effect between training day and luminance levels, $F(9, 12719) = 4.70$, $p < .001$, $\eta_p^2 = .003$ (Table 10). Simple contrast analyses (separate one-way ANOVAs) were conducted to probe the interaction effect of number of days x luminance level. The results indicated significant difference in performance for luminance level 1.20Y ($F(3, 2987) = 6.29$, $p < .001$ and 1.90Y, $F(3, 3459) = 6.29$, $p < .001$, respectively) (Table 15). Post-hoc analysis using the Bonferroni test indicated that participant's performance on luminance difficulty of 1.20Y increased significantly from day 1 (M = .53) to day 3 (M = .62, $p < .01$). In addition, participant's performance on luminance difficulty of 1.90Y increased significantly from day 1 (M = .53) to day 2 (M = .62, p= .03) (Figure 8). Overall, the results provide more evidence for the point of saturation or overtraining occurring after the day 2.

Fifth, we examined the effects of implied motion training on a cortical processing task, namely the subject's critical fusion function threshold (CFFT). Repeated measures ANOVA were conducted to examine changes in CFFT from day 1 to day 4. The Greenhouse-Geisser correction indicated a significant increase in CFFT score from pre-implied motion training (M = 22.23 Hz) to post-implied motion training (M = 24.00 Hz, $F(1, 6) = 9.19$, $p < .05$, $\eta_p^2 = .61$) (Table 14). This finding corroborates similar findings in numerous studies concerning perceptual learning and plasticity (change in CFFT) to subliminal (Watanabe, Náñéz and Sasaki, 2001) and supraliminal directional motion

detection training. In addition, these results show that like real motion subliminal and supraliminal motion training, implied motion training significantly increases cortical processing, as measured by changes in CFFT (Figure 9), despite the decrease in performance the 4 days of training. Note that we did not compare the changes in CFFT to a control group. Previous research has shown that CFFT is stable measurement for visually healthy participants (Seitz, Nanez, Holloway, & Watanabe, 2006). Furthermore, in a similar study, Seitz al., 2006 has shown that CFFT does not increase for n-back (black frame), flash of dots (no motion), and control groups. We reasoned that the within-subject design with many repeated trials over time (four days in the current study) is sufficient to conclude that the changes in CFFT were due to the implied motion task (William, Shadish, Cook, & Campbell, 2002).

Discussion

The goal of this experiment was to expand on previous research that has demonstrated a direct link between low-level visual processing of directional-motion and cortical processing (e.g., flicker perception). A secondary goal was to expand on fMRI studies of implied motion, through psychophysical experimentation. In this study, we examined the effects of an implied motion discrimination task on cortical processing (CFFT). The rationale for examining implied motion as a predictor of cortical processing is based on studies that show a link between implied motion and neural activity in area MT/MST+ (the same area that activates in response to real motion stimuli).

First, we examined whether the stimuli that were designed using custom software in our lab in collaboration with Dr. Aaron Seitz from UC Riverside consisted of valid measures of implied motion. The analysis supported the validity of the stimuli as

indicators of implied motion. The findings show that participants took longer to respond to images with greater articulation, and images with motion blur. The findings suggest that the implied motion stimulus is psychophysically related to information processing (longer reaction time), which is consistent with previous research (Fawcett, Hillebrand, & Singh, 2007).

Second, we examined the validity of the implied motion training. The findings indicated that stimuli were displayed correctly, and it had an impact on participants' performance.

Third, we examined whether performance on the implied motion task parallels the linear pattern found in response to n real motion task. The findings indicated that psychophysical processing of implied motion is different from that for real motion discrimination tasks. That is, exposure to implied motion leads to attainment the saturation point (overtraining) much faster than expected. In this experiment, the point of saturation was reached after day 2 of training (≈1400 frames). In addition, more training was detrimental to performance on day 3 (≈2400 frames) and on day 4 (≈3200 frames). Taken together, the findings show that perceptual learning of the implied motion task occurs quickly as indicated by short amount of training time (number of training days) required to achieve increased performance (brain plasticity/malleability) on the cognitive measure in this study (CFFT). That is, in the current study a limited number of days and training trials on the implied motion task were sufficient for enhancement in CFFT. Previous studies using subliminal and supraliminal real motion required a greater number of days and training trials. Future research should explore possible reasons for this difference.

Fourth, we examined the interaction effect between performance in luminance and number of training days. The findings indicated that performance increased only on day 2 and day 3 for 1.90Y and 1.20Y luminance levels, respectively, providing more evidence for overtraining after day 2.

Five, we examined the relationship between implied motion training and changes in CFFT. In this study we found that implied motion training leads to faster plasticity in CFFT than reported in previous studies using real motion stimuli. This is an interesting finding that should be explored in future studies. The results also suggest that prolonged exposure to directional implied motion is related to higher-level processing. The increase in CFFT occurred over the four days of training despite the decrease in performance on the implied motion task. It is unclear, however, if the increase in CFFT happened during or after the point of saturation, given that CFFT levels were measured in pre- (prior to the start of training on day 1) and post-tests (after completion of training on day 4) only.

The findings in the current study are only generalizable to psychophysical experimentations. More specifically, the changes in performance and reaction time reveal changes in neural network functioning. Neuroimaging (fMRI) might reveal possible changes in neural network structure (increase in neural cell number and synaptic density). In addition, this study looked at healthy participants enrolled in the cognitive rigor and challenges of university life, therefore, the results allow limited generalizability. Future studies should be conducted with participants from the general non-university-go population. Also, would the same findings be found for individuals with low visual acuity or low cognitive abilities?

The findings in this study indicated that the point of saturation occurred after the second day of implied motion training. Future studies may examine the exact point of saturation in regards to number of days and number of trials for implied motion to occur. The same analysis could be done to determine the number of days and trials leading to brain plasticity for critical flicker fusion and other cognitive tasks. In future studies, we also would like to examine the possible interaction effect between point of saturation and increase in CFFT. This would consist of measuring CFFT after each day of implied motion training.

In conclusion, the current study results revealed some interesting finding regarding the relationship between implied motion training (a perceptual task) and changes (plasticity/malleability) on CFFT, a cognitive ability indicator.

Footnotes

[1]The primary visual cortex (V1) is situated in the occipital lobe (located in the back of the brain) and within the calcarine sulcus. Previous research has indicated that V1 is sensitive to orientation, direction-selective information, and low contrast information (Fahle & Poggio 2002).

[2] Observer are first presented with three vertical lines, then they are instructed to identify whether the central line of a bisection stimulus was offset either to the right or to the left (Tartaglia, Bamert, Mast, & Herzog (2009).

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Table 1

Demographic Data

	Cases	Mean	Std. Deviation
Age	7	26.38	9.03
Sex	7	1.57	.535
Education	7	16.29	1.254

Sex: 1= Male, 2 = Female
Education: Number of years in school

Table 2

Mean Differences in Latency by Motion Blur

Visual cues	*M*	*SD*	95% Confidence Interval	
			LB	UB
No Blur	797.43	10.97	775.93	818.93
Motion Blur	840.659	9.251	822.526	858.791
Low	796.91	9.86	777.60	816.23
Medium	813.56	13.80	786.51	840.61
High	846.66	13.26	820.68	872.64

Table 3

Two-way ANOVA: Motion Blur, Speed, and Interaction of Blur x Speed on Latency

	Df	*F*	*P*
Motion blur	1	9.08*	.003
Speed	2	4.54*	.011
Motion Blur x Articulation (interaction)	2	1.11	.328
Error (within)	24626		

Note. * = $p \leq .05$, *** = $p \leq .001$.

Table 4

Tukey's HSD: Mean difference in Latency between Degree of Articulation

Articulation	Medium	High	*Df*
Low	.27	-38.33*	1
Medium	-	-38.61	2

Note. * = $p \leq .05$, *** = $p \leq .001$.

Table 5

One-way ANOVA: Mean Correct by Luminance Level

Source	*Df*	*F*	*P*
Between Groups	3	914.19**	.000
Within Groups	12741		
Total	12744		

Note. * = $p \leq .05$, *** = $p \leq .001$.

Table 6

Tukey's HSD: Mean Difference in Latency between Luminance level

Luminance Level	.90	1.20	1.90
.60	.242*	-.073*	-.346*
.90	-	-.315*	-.588*
1.20	-	-	-.273*

Note. * = $p \leq .05$, *** = $p \leq .001$.

Table 7

Repeated Measures ANOVA: Mean Correct By Training Day

Training day	*Df*	F	η	*p*
	2.999	21.467	.01	.000
Greenhouse-Geisser	13752.387			
Greenhouse-Geisser	13758.000			

Note. * = $p \leq .05$, *** = $p \leq .001$.

Table 8

Polynomial Contrast: Mean Correct By Training Day

Source	Training	*Df*	η	*F*	*p*
Training	Linear	1	5.433	22.17***	.000
	Quadratic	1	10.171	41.36***	.000
	Cubic	1	.009	.04	.849
Error(Training)	Linear	4586	.245		
	Quadratic	4586	.246		
	Cubic	4586	.236		

Note. * = $p \leq .05$, *** = $p \leq .001$.

Table 9

Post Hoc Test using Bonferroni Correction: Mean Correct by Training Day

Training day	Day 2	Day 3	Day 4
Day 1	-.033*	-.016	.046*

Note. * = $p \leq .05$, *** = $p \leq .00$

Table 10

Mean Correct By Day, Luminance, and Interaction between Luminance x Days

Source	*Df*	η	*F*	*p*
Luminance	3	.17	884.00***	.000
Days	3	.000	1.26	.285
Luminance x training days (interaction)	9	.003	4.70***	.000
Error (within)	12719			

Note. * = $p \leq .05$, *** = $p \leq .001$

Table 11

Tukey's HSD: Mean Difference in Latency between Luminance level

Luminance Level	.90	1.20	1.90
.60	.24***	-.07***	-.34***
.90	-	-.34***	-.58***
1.20	-	-	-.27***

Note. * = $p \leq .05$, *** = $p \leq .001$

Table 12

One-way ANOVAs: Mean Correct by Training Split by Luminance Level

Luminance level		*Df*	*F*	*p*
.60	Between Groups	3	1.11	.34
	Within Groups	3408		
	Total	3411		
.90	Between Groups	3	.48	.70
	Within Groups	2865		
	Total	2868		
1.20	Between Groups	3	6.29 ***	.000
	Within Groups	2987		
	Total	2990		
1.90	Between Groups	3	10.20 ***	.000
	Within Groups	3459		
	Total	3462		

Note. * = $p \leq .05$, *** = $p \leq .001$

Table 13

Post Hoc Test using Bonferroni Correction: Mean Correct by Training Day

Luminance	Baseline	Day 2	Day 3	Day 4
.60	Day 1	-.03	.001	.015*
.90	Day 1	.01	.023	.023
1.20	Day 1	.004	-.085*	-.062
1.90	Day 1	-.05*	.03	.05

Note. * = $p \leq .05$, *** = $p \leq .001$

Table 14

Mean Difference in Pre- and Post-CFFT

	Df	*F*	*p*	η
Greenhouse-Geisser	1.000	9.191*	.023	.605
Greenhouse-Geisser (Error)	6.000			

Note. * = $p \leq .05$, *** = $p \leq .001$

Figure 1:

High Articulation

Figure 2:

Medium Articulation

Figure 3:

Low articulation

Figure 4

Frequency of Frame Exposure by Luminance Difficulty

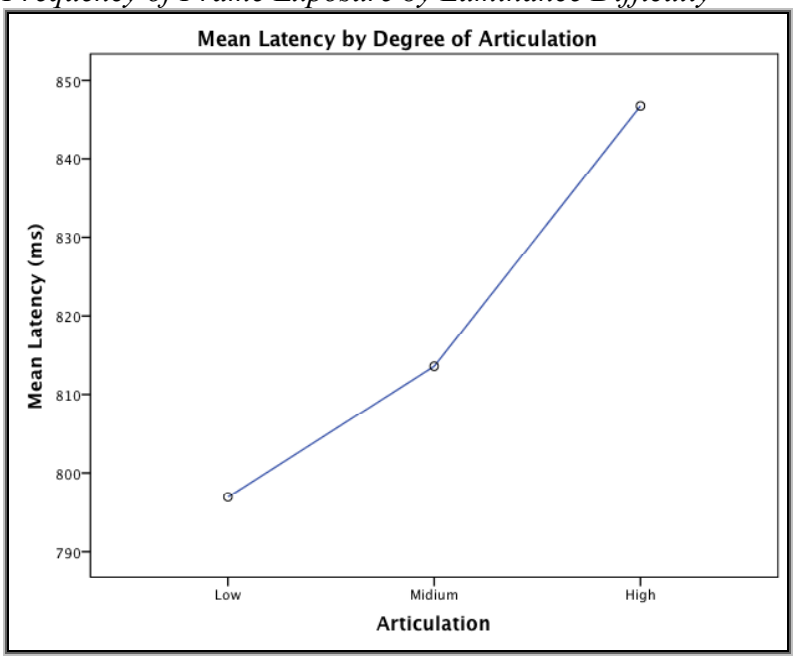

Figure 5

Mean latency of Degree Articulation by Training Day

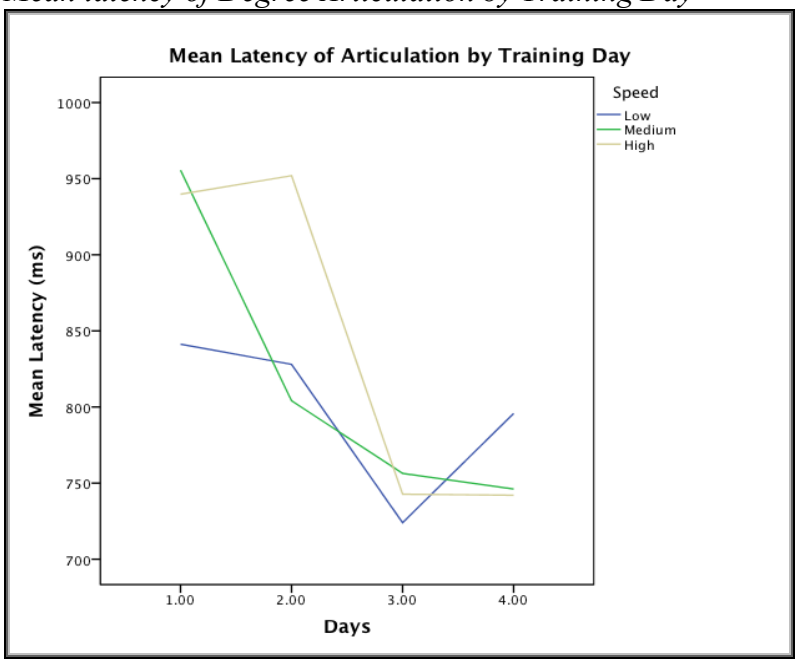

Figure 6

Mean Latency of Motion Blur by Training Day

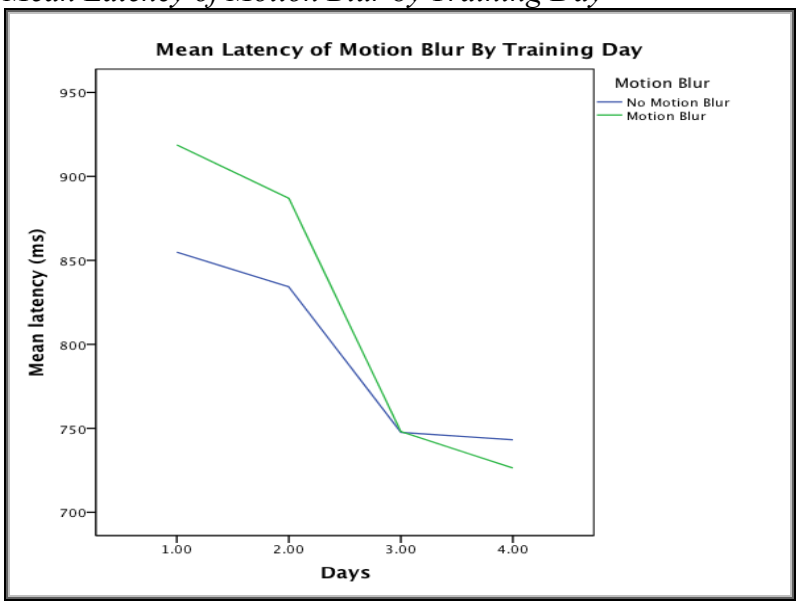

Figure 7

Performance on Implied Motion Task by Training Day

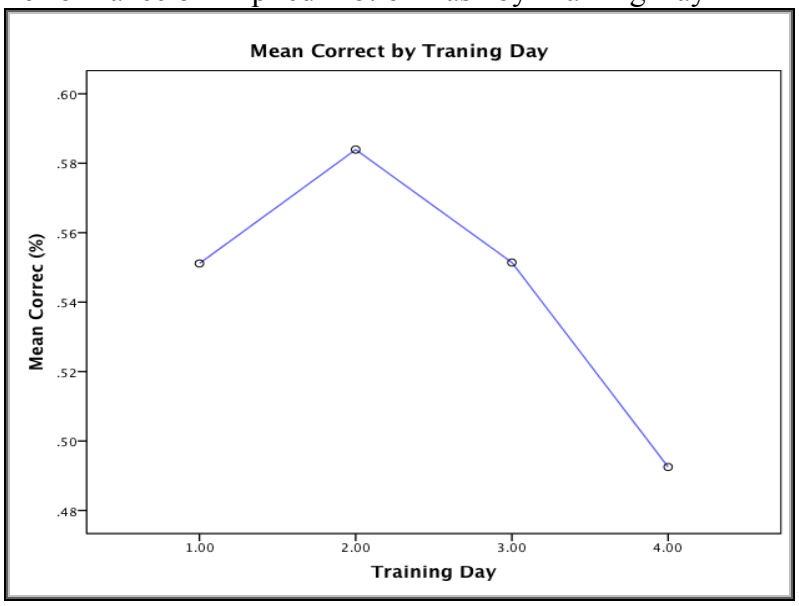

Figure 8

Participants Performance on Luminance Difficulty by Training Day

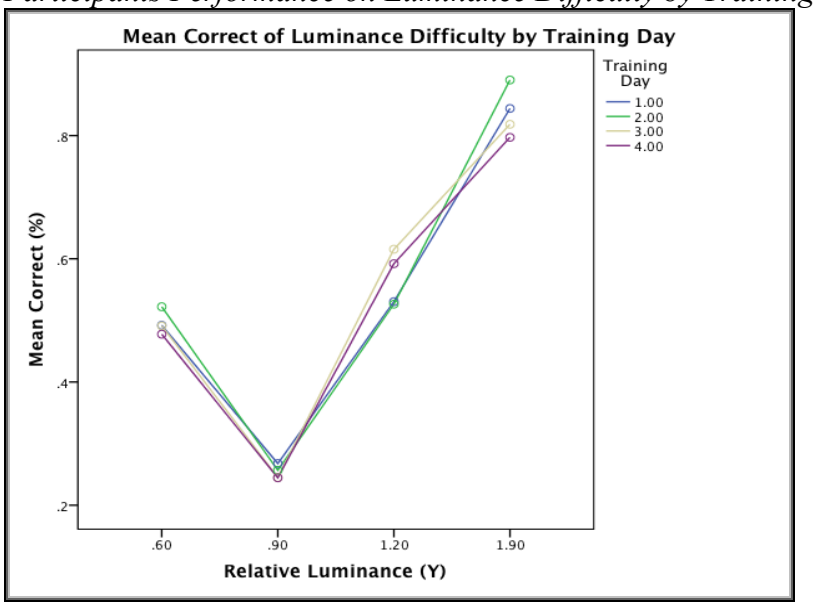

Figure 9

Participants CFFT (Hz) change Day 1 (baseline) vs. Day (4)